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ScienceDirect
Procedia Materials Science 3 (2014) 1965 – 1970
Procedia Materials Science
www.elsevier.com/locate/procedia

20th European Conference on Fracture (ECF20)

Load interaction effects in medium and high strength steels for railway axles

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Abstract

It is well-known from the literature that an interaction effect on crack propagation arises when a specimen or a component is subjected to variable amplitude loading. In dependence of the applied load sequence, a certain amount of retardation or acceleration onto fatigue crack growth rate can then be observed if compared to the constant amplitude case. In the case of structural ductile materials, the interaction phenomenon is mainly addressed by the local plasticity at the crack tip and can be explained, from a global point of view, by adopting the crack closure concept. Considering the applicative case of railway axles, a good correlation between crack growth interaction effects under variable amplitude loading and the amount of plasticity-induced crack closure has been previously derived by the authors, relatively to the standardized EA1N steel. The other standardized European steel for railway axles, a 25CrMo4 grade named EA4T, is instead considered in the present research, as well as an high strenght steel grade. An experimental campaign was carried on this material, using SE(T) specimens, in order to understand and quantify the interaction effects arising from relevant load sequences derived from service. Firstly, tests were performed directly applying the acquired load time history. Eventually, the load history was transformed into an equivalent block loading sequence and applied to different specimens varying the number of cycles of each single block. Finally, the experimental outcomes were modeled adopting both a strip yield model and a simple no-interaction approach, in order to quantify the possible interaction effects. The modeling was carried out considering different experimental techniques for deriving the crack growth and threshold behaviors of the material, i.e. the traditional ΔK-decreasing technique and the compression pre-cracking one.

Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering

Keywords: railway axles, crack propagation, A4T, high strength steels, load interaction effects

1. Introduction

Railway axles are usually designed against fatigue limit (UNI-EN13103 (2012) UNI-EN13104 (2012)), but, due to their very long service life (30 years or even more) and to in-service damages like corrosion or ballast impacts, the approach has moved to a damage tolerant one, as shown by Grandt (2004), Zerbst et al. (2009) and Cantini and Beretta (2011). The problem so moves to the determination of the appropriate maintenance inspection intervals, based

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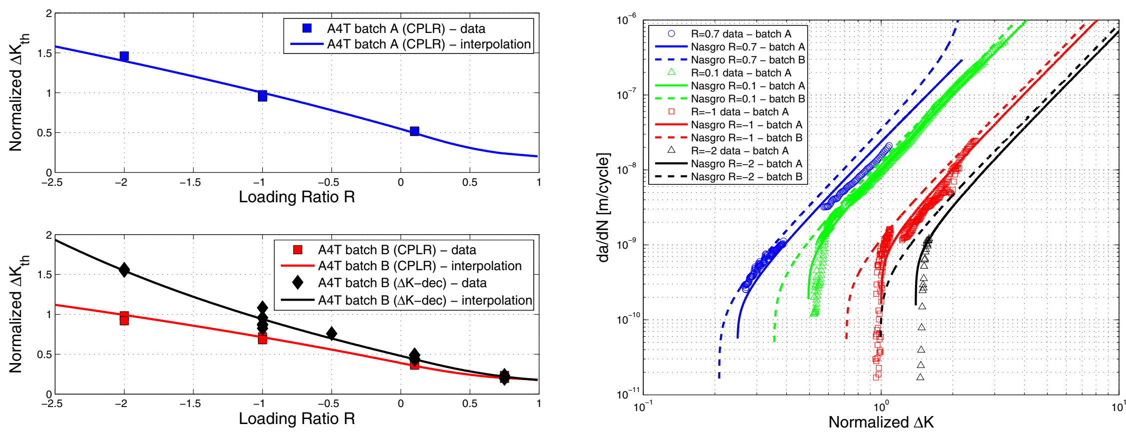
Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering
doi:10.1016/j.mspro.2014.06.316

on crack growth life predictions and the adopted non-destructive testing technique (Cantini et al. (2007)). It is well known from the literature that an interaction effect on crack propagation arises when a specimen or a component is subjected to variable amplitude (VA) loading, like railway axles are (Luke et al. (2011), Mädler (2013)). In dependence of the applied load sequence, a certain amount of retardation or acceleration onto fatigue crack growth rate can be observed, if compared to the constant amplitude (CA) case. In the case of structural ductile materials, this interaction phenomenon is mainly addressed by the local plasticity at the crack tip and can be explained, from a global point of view, by adopting the plasticity-induced crack closure concept (Schijve (1960), Bannantine et al. (1990)), as shown by Beretta and Carboni (2011).

In order to quantify the phenomenon, crack growth tests under variable amplitude loading were carried out onto companion (Conle and Nowack (1977)) SE(T) specimens, showing the same constraint effect at the crack tip of a railway axle (Carboni et al. (2008)), made of medium (two batches of A4T material) and high strength steel (HSS). The variable amplitude loading applied was in the shape of time history or equivalent load spectrum, with different lengths of the blocks, in order to check the eventual presence of an additional retardation effect due to the load sequence. Crack growth simulations were then carried out, trying to approximate at best the experimental evidence, adopting the threshold definition from different experimental techniques, CPLR and ΔK-decreasing. Firstly, crack growth simulations were carried out by the meaning of the strip-yield model, then a simple approximation was adopted, trying to match the experimental outcomes by a no-interaction model.

2. Crack growth behavior of the tested materials

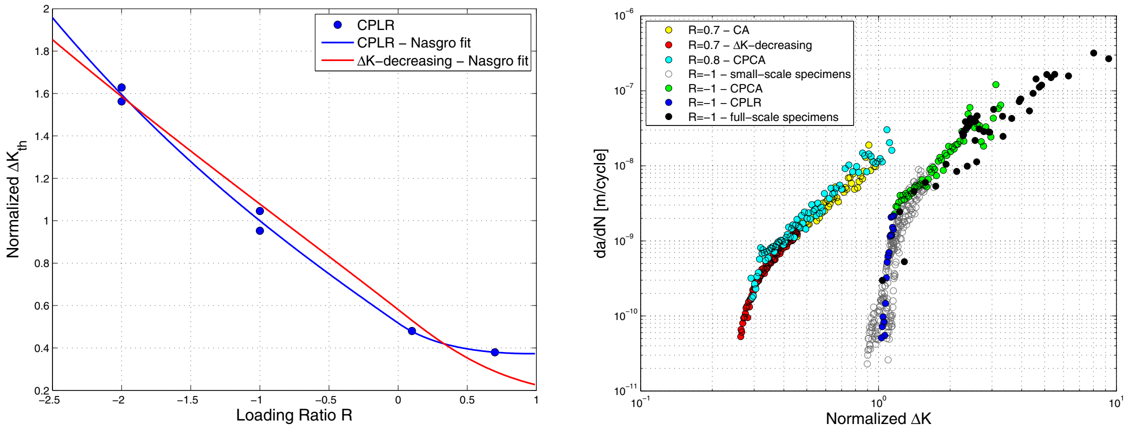
Three steel grades were adopted in the present research: two batches of medium strength steel grade A4T (batch A and batch B), which crack growth behavior at CA is showed in Figure 1, normalized against ΔK_{th} at R=-1 of batch A, and a high strength steel grade HSS, which crack growth behavior at CA of this material is shown in Figure 2. As can be seen, while there is almost no difference in the thresholds generated applying CPLR or ΔK-decreasing experimental methodologies for the high strength steel grade, the medium strength steel A4T batch B, tested with both CPLR and ΔK-decreasing, showed a threshold trend, by ΔK-decreasing, about 15% higher than CPLR at R=-1.



(a) Trend of normalized threshold SIF with stress ratio (b) Normalized crack growth curves

Fig. 1. Normalized crack growth behavior of the considered A4T materials

No threshold experiments were carried out onto A4T batch A steel grade adopting the ΔK-decreasing methodology; the increase of ΔK_{th} at R=-1, for prospective tests with ΔK-decreasing, was estimated to be approximately 15% from A4T batch B data.



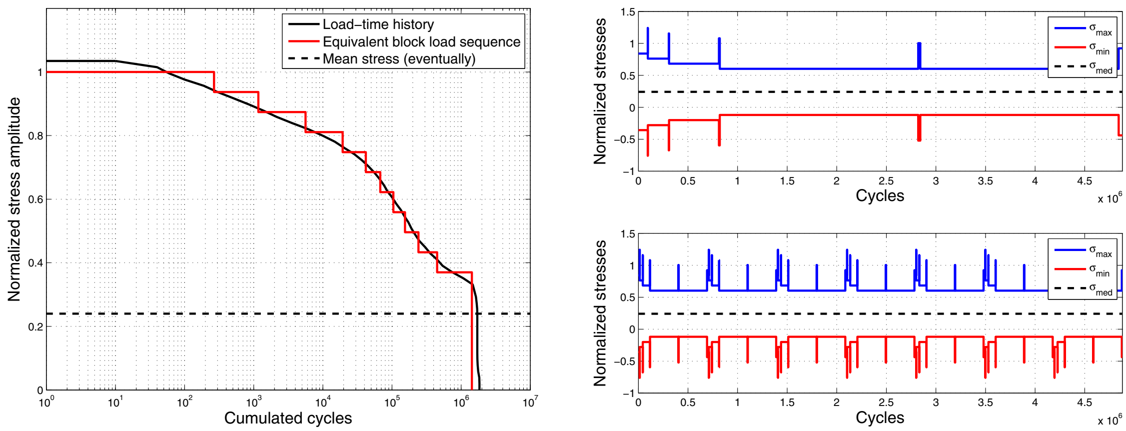
(a) Trend of normalized threshold SIF with stress ratio

(b) Normalized crack growth curves

Fig. 2. Normalized crack growth behavior of the considered high strength steel grade HSS

3. Variable Amplitude loading tests

The specimen's geometry adopted for VA testing was a single edge-notched SE(T) specimen for tensile application, having width equal to 50 mm and thickness equal to 20 mm; the initial notch size, obtained by EDM, was 6 mm. Specimens were pre-cracked in compression on a mono-axial universal testing facility equipped with a 250 kN load cell. Crack length was measured in real-time with a RUMUL Fractomat control unit by using two 20 mm crack gages glued on both sides of each specimen after pre-cracking.



(a) Load spectrum

(b) Load sequences: long blocks (up) against short ones (down)

Fig. 3. Normalized VA loadings, in the shape of block loading sequences derived from real service (case of $R \neq -1$)

The applied VA loading was in the shape of both time history or equivalent load spectrum, shown in Figure 3a. When applying the load spectrum, a Gaßner (1941) load sequence, two different lengths of the blocks were applied (Figure 3b), considering the initial number of cycles and this length divided by seven; all the details of the carried out experiments under VA loading are shown in Table 1. Eventually, but it was done only for A4T batch A, a mean stress was added to the spectrum, simulating the effect of the press-fit.

A first interesting result, appearing evidently from the plots of Figures 4b, 5b and 6b, is that there is a good agreement between crack propagations obtained applying time history against block loading, or long blocks against short ones. This is true for all the three steel grades tested.

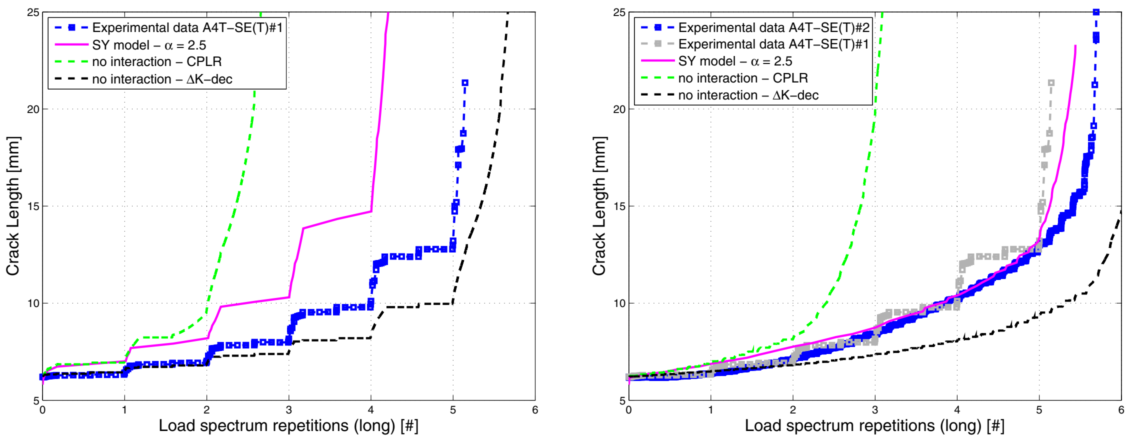
4. Crack growth simulations

Crack growth simulations were firstly carried out by the meaning of the Strip-Yield model, as implemented in the commercial software Nasgro (2006). The threshold trend from CPLR experimental methodology was adopted, and the experimental effective crack growth curve (conventionally taken at R=0.7), for each material, was provided as input. Then, a simpler attempt to match lifetime predictions to the experiments consisted in a no-interaction model, adopting both CPLR and ΔK-decreasing thresholds.

The α values for strip yield simulations were $\alpha = 2.5$ for A4T and $\alpha = 1.75$ for HSS. These values allowed us to obtain a good description of crack growth curves at R=-1 onto SE(T) specimens (Regazzi (2014), Beretta et al. (2014)).

Table 1. Summary of the VA experiments carried out

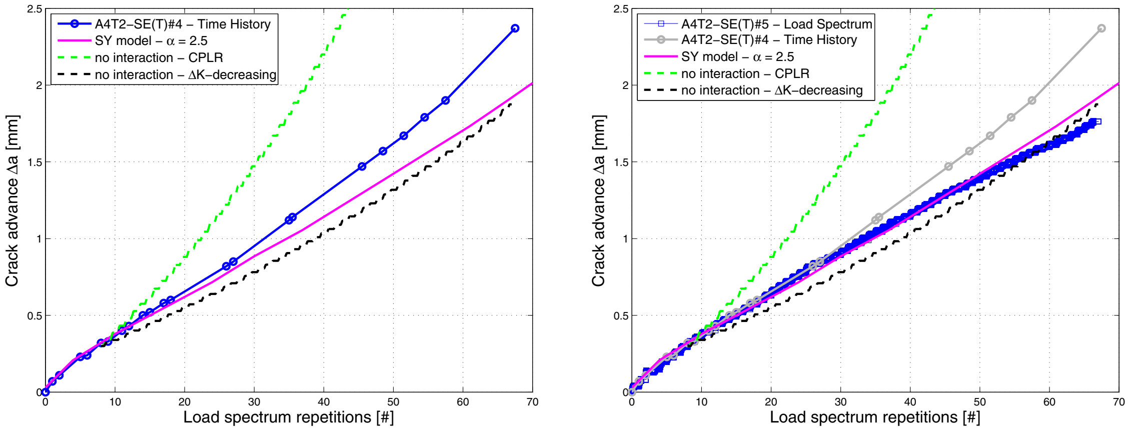
Specimen	Material	VA loading	S_{max}/S_{y-cyc}	$\Delta K_{max}/\Delta K_{th}$
A4T-SE(T)#1	A4T batch A	long blocks ($R \neq -1$)	0.21	2.0
A4T-SE(T)#2	A4T batch A	short blocks ($R \neq -1$)	0.21	2.0
A4T2-SE(T)#4	A4T batch B	time history ($R = -1$)	0.20	1.2
A4T2-SE(T)#5	A4T batch B	block loading ($R = -1$)	0.20	1.2
HSS-SE(T)#1	HSS	time history ($R = -1$)	0.11	1.4
HSS-SE(T)#2	HSS	block loading ($R = -1$)	0.11	1.4



(a) Specimen A4T-SE(T)#1 (b) Specimen A4T-SE(T)#2

Fig. 4. Crack growth simulations, carried out adopting the Strip-Yield and the no-interaction models, against the experimental evidence for A4T 'batch A' material

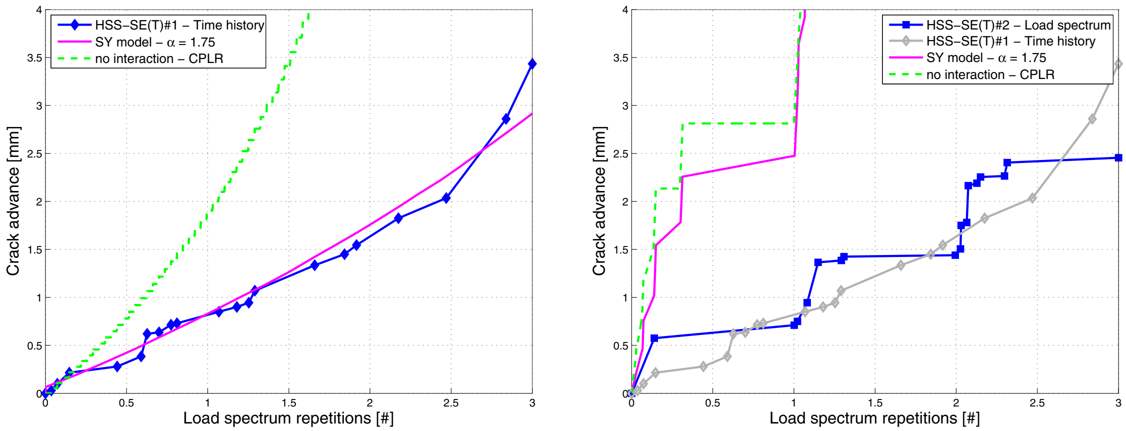
Concerning the strip-yield model, the parameter α was fixed at 2.5, according to the Nasgro (2006) manual. Carboni et al. (2008) suggested a value of α close to 3 for the modified SE(T) specimens made of A1N, but the evidence for the A4T steel grade, here, is in contradictions with this indication. An α value close to 2.5 is adequate for crack growth predictions for both specimens made of A4T batch A, thus remaining on the safe side, as in Figure 4; both specimens show a similar amount of retardation against the no-interaction model, staying in between the CPLR (too conservative) and the ΔK-decreasing (not conservative). As can be appreciated from Figure 4b, the results of the two tests, against long and short blocks, are not distinguishable.



(a) Specimen A4T2-SE(T)#4 (b) Specimen A4T2-SE(T)#5

Fig. 5. Crack growth simulations, carried out adopting the Strip-Yield and the no-interaction models, against the experimental evidence for A4T 'batch B' material

The A4T batch B material showed a behavior nearly identical to the first batch: the experimental results coincide, as in Figure 5, applying both time history and equivalent block loading. Moreover, an α parameter for the strip-yield model equal to 2.5, the same value obtained for the first batch of A4T steel grade, is again adequate to well predict the experimental evidence. Regarding the no-interaction model, simulations were carried out starting from the crack length at which the crack growth was definitely stabilized (upward curvature in a-N plot). Also for this material, the experiments stay in between the two no-interaction simulations adopting thresholds from CPLR and ΔK-decreasing.



(a) Specimen HSS-SE(T)#1 (b) Specimen HSS-SE(T)#2

Fig. 6. Crack growth simulations, carried out adopting the Strip-Yield and the no-interaction models, against the experimental evidence for high strength steel HSS

Also the high strength steel tested, shown in Figure 6, returned in comparable crack advance from both time history and load spectrum, without any additional retardation effect.

Specimen HSS-SE(T)#1, tested against time history loading, could be well represented by the chosen α parameter, while specimen HSS-SE(T)#2, tested against block loads, was not well predicted by the strip yield model with the same value of α. Even if the two specimens show comparable crack propagation trends at a global level, as visible in Figure 6, the sequence of loads is different, requiring a different SY modellization; regarding the second specimen, a very low α value is required to force the crack to stop during the long blocks at low stress amplitude.

Again, the same behavior appears from the simpler model: a no-interaction model, adopting the thresholds from CPLR results in predictions which are too conservative, especially when applied to a long block loading sequence.

5. Concluding remarks

The effect of Variable Amplitude loading onto crack propagation was considered, relatively to three different materials: two medium strength steel batches (A4T) and a high strength steel grade, typically adopted in the railway axle production, were considered. The results of the research can be so summarized:

- no evident retardation effect arose in dependence of the shape of the VA loading, for all the three steel grades tested: results derived applying time history against block loading, or long blocks against short ones, are always in good agreement; this permits to apply load sequences composed by long blocks to the full-scale specimens (where it is not feasible to apply time history), without affecting the results;
- the experimental evidence is always in between the two no-interaction simulations considering thresholds from CPLR (conservative predictions) and ΔK-decreasing (non conservative predictions); this is true for the A4T steels, where an appreciable distance between the thresholds from the two methodologies appeared; for HSS, CPLR always resulted in conservative predictions;
- an evident retardation effect clearly appears, in repect to the no-interaction predictions adopting CPLR thresholds; this retardation effect is justified by the strip yield simulations carried out.

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